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The Physics of Black Hole X-ray Transients

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Abstract

The most plausible mechanism for triggering the outburst of black hole candidate X-ray transients is the ionization thermal instability. The disk instability models can give the observed mass flow in quiescence, but not the X-ray spectrum. Self-irradiation of the disk in outburst may not lead to X-ray reprocessing as the dominant source of optical light, but may play a role in the "reflare." The hard power-law spectrum and radio bursts may be non-thermal processes driven by the flow of pair–rich plasma from the disk at early times and due to the formation of a pair–rich plasma corona at late times. The repeated outbursts suggest some sort of clock, but it is unlikely that it has anything to do with a simple X-ray heating of the companion star.

1. Introduction

Many of the X-ray novae discovered in recent years are black hole candidates by direct measure of their mass function or by shared properties (McClintock and Remillard 1986, Tanaka & Lewin 1995 and references therein). Among the commonly observed features are a primary outburst maximum, a "secondary reflare", 50−80 days after maximum, and a "third broad bump" in the decay, a few hundred days later. The first two features are especially marked in the soft X-ray and are probably associated with the geometrically thin, optically thick accretion disk. The latter is associated with the hard power-law source that may be a signature of black hole accretion. Nova Per and Nova Vela revealed repeated "mini-outbursts" after the third, broad

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bump (Callanan *et al.* 1995, Della Valle, Benetti, and Wheeler 1996). Two "super-luminal sources", Nova Oph 1993 (GRS 1915+105) and Nova Sco 1994 (GRO J1655-40) display jet-like outflow in the radio (Mirabel & Rodriguez 1994, Harmon *et al.* 1994) and radio activity is commonly associated with all outbursts (Han and Hjellming 1992).

The power-law flux rises in Nova Muscae before the soft X-ray, but declines rapidly so that the soft flux dominates the total power at its maximum Miyamoto *et al.* 1993. There is a strong dip in the hard flux just before the observations of a transient line at 480 Kev (Sunyaev *et al.* 1992; Goldwurm *et al.* 1992). This feature has been associated with a red–shifted positron annihilation line. Although it occurs at the rest wavelength of a Li de-excitation line (Martín *et al.* 1994), the lack of other de-excitation lines and the association of the feature with the modulation of the hard power-law flux suggests that annihilation is still a reasonable interpretation. The secondary reflare is essentially a feature of the soft flux and hence of the accretion disk. It occurs just as the hard power-law component reaches a minimum, for reasons that are not understood. At about 150 days in Nova Muscae, the disk component of the soft flux plummets and the power, including that in soft X-rays, becomes dominated by the power-law source at the "third broad bump."

2. Disk Irradiation

The disk instability (Mineshige and Wheeler 1989) naturally gives a rapid rise and slower decline in the soft X-ray and optical. It can give an exponential decay as observed in some sources, but the origin of this is under debate (Cannizzo, Chen, and Livio 1996). The mass transfer from the companion in A0620-00 greatly exceeds that attributed to the soft X-rays from the inner disk (Marsh, Robinson and Wood 1994; McClintock, Horne, and Remillard 1995). This shows that the disks are not in steady state in quiescence, a principle prediction of the disk instability models.

In principle, strong irradiation can keep the disk ionized and prevent the disk instability. We find that for models that approximately match the light curve of A0620-00 and similar sources that the irradiation can not be that severe (Kim, Wheeler and Mineshige 1996a,b, and the associated contributed paper to this conference). The irradiation even at modest levels can subtly affect the disk evolution by prolonging the disk in the intermediate, metastable partially ionized, "stagnation" state. One especially interesting manifestation of this is that some regions of the disk can be driven from the metastable state back to the hot, ionized state. This causes them to be brighter intrinsically and to intercept more irradiation. In our current models the associated optical flare can match the time and amplitude of the optical component of the reflare in A0620-00. We do not get appreciable modulation of the mass flow through the inner edge of the disk and so do not get an obvious increase in the soft X-ray flux, one of the defining characteristics of the reflare.

The models that match the light curve of A0620-00 have the ignition of the thermal instability in the outer portions of the disk. This implies that the optical light curve should always rise before any harder flux associated with the increase of the mass flow in the inner portions of the disk. The question of whether the hard or soft X-ray flux should increase first depends on a better understanding of the origin of the hard flux.

These models also have the interesting property that the cooling wave slows as the density declines, but never reaches the inner edge of the disk. The inner disk thus always remains in the hot ionized state. The mass flow rates are $\sim 10^{12}$ g s^{-1}, close to those constrained by observations in quiescence (Marsh *et al.* 1994; McClintock *et al.* 1995). The temperatures we derive, are, however, less than 300,000 K, whereas the quiescent X-ray spectrum implies a temperature of about $2{\times}10^6$ K.

Van Paradijs and McClintock (1994) have argued that, as for the LMXB, the optical flux of the black hole candidates is due to reprocessing of X-rays. This is not clear since the black hole systems are transient and the flux ratio will vary in time. In addition, the disk instability models for X-ray transients give an adequate amount of optical light even with no irradiation. For the same orbital period, black hole disks are larger than neutron star disks. This mass-dependent factor alone could make a black hole disk a factor of five to ten larger in optical emitting area than for a neutron star. Van Paradijs and McClintock (1994) argue that L_{opt} is proportional to $L_x^{1/2}$. We have constructed steady state models with no irradiation and found that the optical luminosity depends more steeply on L_x than that with increasing disk radius. Furthermore, we have computed time-dependent, non-irradiated models and found that on the decline the locus of optical and X-ray flux is even slightly steeper than the steady state models. This subject requires study in greater depth.

3. The Reflare and Other Bumps

The "secondary reflare" is a rather common (though not universal) phenomenon of the black hole candidates and has never been observed in a neutron star system. It is thus worthy of understanding even though it is a secondary effect compared to the primary outburst.

Chen, Livio and Gehrels (1993) discuss the possibility that the mass transfer rate from the companion can be modulated by irradiation from the inner disk. It is not clear that a burst of mass transfer would give either the observed optical or X-ray features. Even a sharp burst of added mass will be spread by the finite viscous response of the disk (especially when the outer parts of the disk are in the cold state) so that any later effect in the X-rays will be delayed with respect to the optical and very spread out in time. There are also questions of whether the disk blocking invoked by Chen *et al.* to account for the delay of the secondary reflare is consistent with their estimates

of mass transfer and energetics that depend on irradiating the companion. Similar issues arise in their model for the third broad bump.

Augusteijn, Kuulkers and Shaham (1993) suggest an oscillation of the light curve in the decay in which each successive burst is a "reflection" of the previous burst that heats the companion and drives more mass transfer after some time delay. This model seems to be remarkably reminiscent of the "mini-outbursts" in Novae Per and Nova Vela. Augusteijn *et al.* even predicted bursts in Nova Per in August 1993 and December 1993, (but also 21 April) as observed. Augusteijn *et al.* deserve great credit for drawing attention to the fact that there may be some "clock" underlying the bursts in Nova Per and perhaps other objects, but there are still open questions concerning their particular model. Augusteijn *et al.* did not clearly differentiate the "second reflare" from the "third broad bump" as we are defining them here. They adjust parameters of their model to fit the second reflare of GS 2000+25 in one illustration of their model, but then calibrate the model of Nova Per on the third broad bump in order to "predict" the later outbursts in that system. It is not at all clear that the second reflare and the third broad bump involve similar physics. The models of Augusteijn *et al.* also do not consider the state of the disk, especially in its cool, quiescent, low-viscosity state, in a self-consistent way.

We do not yet have a complete understanding of the physical mechanism of the secondary reflare (or subsequent flares). No model yet proposed can naturally account for why the secondary reflare seems to coincide with the drop in the hard X-ray flux. Nevertheless, the irradiated models we have investigated show that effects in the disk alone can give optical outbursts that may be related to the optical flares seen. They also give us a new perspective from which to consider questions of the irradiation of the companion.

Unlike the pictures proposed by Chen *et al.* (1993) and Augusteijn *et al.* (1993), our current models show that the direct X-ray irradiation of either the outer disk or the L_1 point is blocked by the inner disk throughout the decay phase prior to the secondary reflare. The hypothesis of the X-ray-irradiated mass transfer burst models, that the L_1 point be irradiated, therefore, seems to be contradicted by the shadowing given in the current models (Kim *et al.* 1996a,b).

4. Advection

Narayan, Yi, and McClintock (1996) obtain a fit to both the optical and X-ray spectra of A0620-00 in quiescence by invoking a hot two-temperature advective disk solution in the inner disk matched to a steady state disk in the outer portions that provides the optical luminosity. The advective solution, however, is of low efficiency and requires a mass flow rate of 4×10^{14}g s^{-1}, much higher than the estimates based on steady state, geometrically thin,

optically thick disks by Marsh *et al.* (1994) and McClintock *et al.* (1995) and much higher than the quiescent flow rates we obtain in these models. The steady-state disks appended to the advection solutions are not consistent with the quiescent state of the disk being modeled. The advection solutions require some means of severely depleting the surface density of the inner portions of the disk as the disk approaches quiescence. It is difficult to see how such a solution matches physically in terms of the surface density and angular momentum with the outer geometrically thin, quiescent, Keplerian disk.

5. The Hard Power Law, Radio Outbursts, and Positrons

The hard power law component is commonly assumed to be a Comptonized thermal spectrum. Such a simple model can fit some objects at some epochs, but that does not make it unique or correct. Such models ignore the obvious evidence for non-thermal particles and magnetic fields implied by the common radio outbursts that are frequently associated with the X-ray bursts (Han and Hjellming 1992). The recent super-luminal sources are only the most extreme example. It is most likely that the non-thermal particles and magnetic fields arise in the disk and hence must be incorporated into models of the hard power-law emission.

The soft X-ray component that probably arises in the accretion disk peaked more slowly than the hard power law flux in Nova Muscae. This may mean that the inner disk was incomplete in quiescence or the early phase of the outburst. The radius of the geometrically thin, optically thick disk may have shrunk in response to increased mass flow attendant with the disk instability in the outer disk, thus giving rise to the delayed rise of the soft flux.

The first flare of the hard flux in systems like Nova Muscae can be associated with a non-thermal, magnetic, pair-rich outflow (Moscoso and Wheeler 1993). This phase shows QPO's, correlated radio synchrotron bursts, and at least in Nova Muscae, the line feature that is plausibly associated with annihilation. If this is the annihilation line, then it is much too narrow to represent annihilation in the region where positrons are created and hence implies flow of some kind.

The "third bump," as we have defined it here, may more closely resemble a quasi-static corona of the sort frequently modeled in the literature (Mineshige, Kusunose, and Matsumoto 1995). The fact that the disk component of the soft X-ray flux declines as this late hard component comes in strongly suggests that the corona is displacing the geometrically thin disk. With a larger effective inner radius, the disk simply becomes too cool to emit soft X-rays.

Moscoso is constructing a model to better understand the source of the outflow in the primary outburst. This model consists of an inner hot, pair-rich

corona represented by a single zone. Above this corona, photon annihilation will generate electron/positron pairs and associated annihilation. The parallel component of the average momentum of the photons that produce pairs is assumed to represent the bulk outflow momentum of pairs. The remaining momentum is randomized to provide the thermal component of the pair energy. Account will be taken of both the isotropic and anisotropic Comptonization. This simple model will give an estimate of the typical flow time scales, speeds, and the optical depth so that annihilation line profiles can be estimated.

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References

Augusteijn, T., Kuulkers, E., & Shaham, J. 1993, A&A, 279, L13
Callanan, P. J. *et al.* 1995, submitted to ApJ
Cannizzo, J. K., Chen, W., & Livio, M. 1996, ApJ, in press
Chen, W., Livio, M., & Gehrels, N. 1993, ApJ, 408, L5
Della Valle, M., Benetti, S. & Wheeler J. C. 1996, A&A, in preparation
Goldwurm, A. *et al.* 1993, ApJ, 389, L79
Han, X., & Hjellming, R. M. 1992, ApJ, 400, 304
Harmon, B. A. *et al.* 1995, Nature, 374, 703
Kim, S.-W., Wheeler, J. C., & Mineshige, S. 1995a, in preparation
Kim, S.-W., Mineshige, S., & Wheeler, J. C. 1996b, in preparation
Marsh, T. R., Robinson, E. L., & Wood, J. H. 1994, MNRAS, 266, 137
Martín, E. L., Rebolo, R., Casares, J., & Charles, P. A. 1994, ApJ, 791, 1994.
McClintock, J. E., Horne, K., & Remillard, R. A. 1995, ApJ, 442, 358
McClintock, J. E., & Remillard, R. A. 1986, ApJ, 308, 110
Mirabel, I. F., & Rodriguez, L. F. 1994, Nature, 371, 46
Mineshige, S., Kusunose, M., & Matsumoto, R. 1995, ApJ, 445, L43
Mineshige, S., & Wheeler, J. C. 1989, ApJ, 343, 241
Miyamoto, S. *et al.* 1993, ApJ, 403, L39
Moscoso, M. D. and Wheeler, J. C. 1993, in Interacting Binary Stars, ed. A. W. Shafter (San Francisco: ASP), 100
Sunyaev, R. *et al.* 1992, ApJ, 389, L75
Tanaka, Y. and Lewin, W. H. G., 1995 in X-Ray Binaries, eds. W. H. G. Lewin, J. Van Paradijs, & E. P. J. Van Den Heuvel (Cambridge: Cambridge University Press), 126
Van Paradijs, J. and McClintock, J. E. 1994, A&A, 290, 133.